

2 THE MAGNETIZATION IN DOMAINS AND BULK MATERIALS

INTRODUCTION

Thus far, we have discussed the factors that contribute to the atomic and ionic moments and the effect of their magnetic interactions on the moments of the various crystal lattices. These moments are the maximum values or those measured under saturation conditions, at 0 K., that is, with complete alignment of the net magnetic moments. These values we found were intrinsic properties, that is, they depended only on chemistry and crystal structure (and of course, temperature). We have not discussed the important aspects of domain and bulk material magnetizations. In this chapter, we will expand our scope from the microscopic moment to the larger moment (in domains) and finally to the macroscopic bulk magnetization. Once these are described, we can then turn to the topics of magnetization mechanisms, magnetization reversal, and ultimately to cyclic magnetization, as in alternating current operation. To obtain a clear picture of these topics, the use of domain theory and domain dynamics is indispensable. This chapter will first discuss these subjects and show how they lead to the bulk magnetic properties.

THE NATURE OF DOMAINS

In a ferromagnetic domain, there is parallel alignment of the atomic moments. In a ferrite domain, the net moments of the antiferromagnetic interactions are spontaneously oriented parallel to each other (even without an applied magnetic field). The term, spontaneous magnetization or polarization is often used to describe this property. Each domain becomes a magnet composed of smaller magnets (ferromagnetic moments). Domains contain about 10^{12} to 10^{15} atoms and their dimensions are on the order of microns (10^{-4} cm.). Their size and geometry are governed by certain considerations. Domains are formed basically to reduce the magnetostatic energy which is the magnetic potential energy contained in the field lines (or flux lines as they are commonly called) connecting north and south poles outside of the material. Figure 2.1 shows the lines of flux in a particle with a single domain. The arrows indicate the direction of the magnetization and consequently the direction of spin alignment in the domain. We can substantially reduce the length of the flux path through the unfavorable air space by splitting that domain into two or more smaller domains. This is shown in Figure 2.2. This splitting process continues to lower the energy of the system until the point that more energy is required to form the domain boundary than is decreased by the magnetostatic energy change. When a large domain is split into n domains, the energy of the new structure is about $1/n$ th of the single domain structure. In Figure 2.2, the moments in adjacent domains

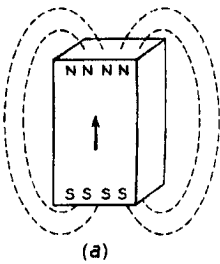


Figure 2.1-Lines of force in a particle of a single domain

are oriented at an angle of 180° to each other. This type of domain structure is common for materials having a preferred direction of magnetization. In other instances, especially where the cubic crystal structure is involved, certain oriented

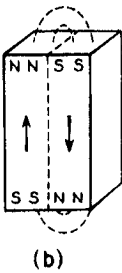


Figure 2.2- Reduction of magnetostatic energy by the formation of domains

domain configurations may occur which lead to lowering of the energy of the system. One of these is shown in Figure 2.3. These triangular domains are

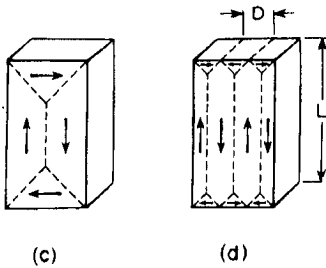


Figure 2.3- Elimination of magnetostatic energy by the formation of closure domains

called closure domains. In this configuration, the magnetic flux path never leaves the boundary of the material. Therefore, the magnetostatic energy is reduced. This type of structure may also be found at the outer surfaces of a material. The size and shape of a domain may be determined by the minimization of several types of energies. They are;

1. Magnetostatic Energy
2. Magnetocrystalline Anisotropy Energy
3. Magnetostrictive Energy
4. Domain Wall Energy

In addition, certain microstructural imperfections such as voids, non-magnetic inclusions and grain boundaries may also affect the local variations in domain structure.

Magnetostatic Energy

The magnetostatic energy is the work needed to put magnetic poles in special geometric configurations. It is also the energy of demagnetization. It can be calculated for simple geometric shapes. For an infinite sheet magnetized at right angles to the surface the equation (Bozorth 1951) for the magnetostatic energy per cm^3 is ;

$$E_p = 2 \pi M_s^2 \quad [2.1]$$

Néel (1944) and Kittel (1946) have calculated the magnetostatic energy of flat strips of thickness, d , magnetized to intensity, M , alternately across the thickness of the planes. The equation is;

$$E_p = 0.85 d M^2 \quad [2.2]$$

The calculations for other shapes come out with the general formula;

$$E_p = (\text{Constant}) \times d M_s^2 \quad [2.3]$$

Therefore the magnetostatic energy is decreased as the width of the domain decreases. This mathematically confirms our assumption that the splitting of domains into smaller widths decreases the energy from the magnetostatic view. In fact, the energy of the domain structure is one thousandth that of a similar sized single domain.

Magnetocrystalline Anisotropy Energy

Most matter is crystalline in nature; that is, it is composed of repeating units of definite symmetry. Let us take a common geometrical configuration that may form the smallest repeating unit, namely a cube. Atoms or molecules are usually located at corners of the cube and in addition, at either the center of the cube or at the centers of the 6 faces. In most magnetic materials, to varying degree, the domain magnetization tends to align itself along one of the main crystal directions. This direction is called the easy direction of magnetization. Sometimes it is an edge of the cube

and at other times, it may be a body diagonal. The difference in energy of a state where the magnetization is aligned along an easy direction and one where it is aligned along a hard direction is called the magnetocrystalline anisotropy energy. This magnetocrystalline anisotropy energy is also that needed to rotate the moment from the easy direction to another direction. The energy of the domain can be lowered by this amount by having the spins (ferromagnetics) or moments (ferrimagnetics) align themselves along these directions of easy magnetization. In materials with high uniaxial anisotropy energy the moment of one domain is usually aligned along an easy direction of magnetization. Then, the adjacent domain will have the same tendency to align along the same axis but in the opposite direction. Even in materials with lower anisotropy, the 180° wall is often found. In crystals of cubic symmetry, where many of the major axes are at right angles (such as the cube edges) the 90° domain wall is also a reasonable possibility.

Magnetocrystalline anisotropy is due to the fact that there is not complete quenching of the orbital angular momentum as we postulated originally. With a small orbital moment that is mechanically tied to the lattice, the spin system can couple to it and therefore indirectly affect the lattice or the dimensions of the material.

Magnetostrictive Energy

When a magnetic material is magnetized, a small change in the dimensions occurs. The relative change is on the order of several parts per million and is called magnetostriction. The converse is also true. That is, when a magnetic material is stressed, the direction of magnetization will be aligned parallel to the direction of stress in some materials and at right angles to it in others. The energy of magnetostriction depends on the amount of stress and on a constant characteristic of the material called the magnetostriction constant.

$$E = \frac{3}{2} \lambda \sigma \quad [2.4]$$

where; λ = magnetostriction constant
 σ = Applied stress

The convention of the sign of the magnetostriction constant is such that if the magnetostriction is positive, the magnetization is increased by tension and also the material expands when the magnetization is increased. On the other hand, if the magnetostriction is negative, the magnetization is decreased by tension and the material contracts when it is magnetized. Magnetostriction as in the case of anisotropy is due to incomplete orbital quenching and the so-called spin-orbit, L-S or Russell Saunders coupling. Stresses can be introduced in ferrites by mechanical and thermal operations such as firing, grinding, and tumbling. These stresses also affect the directions of the moments locally depending on the distribution of the stresses.

Domain Wall Energy

Although Weiss (1907) first came up with the idea of the strong molecular field producing regions of oriented atomic moments or of spontaneous magnetization, it was Bloch (1932) who was the first to present the idea of magnetic domains, with

domain walls (sometimes called Bloch walls) or boundaries separating them. In the domain structure of bulk materials, the domain wall or boundary is that region where the magnetization direction in one domain is gradually changed to the direction of the neighboring domain. If δ is the thickness of the domain wall which is proportional to the number of atomic layers through which the magnetization is to change from the initial direction to the final direction, the exchange energy stored in the transition layer due to the spin interaction is;

$$E_e = kT_c/a \quad [2.5]$$

where kT_c = Thermal energy at the Curie point

a = Distance between atoms

Therefore the exchange energy is reduced by an increase in the width of the wall or with the number of atomic layers in that wall. However, in the presence of an anisotropy energy or preferred direction, rotation of the magnetization from an easy direction increases the energy so the wall energy due to the anisotropy is :

$$E_k = k \delta \quad [2.6]$$

In this case, the energy is increased as the domain width or number of atomic layers is increased. The two effects oppose each other and the minimum energy of the wall per unit area of wall occurs according to the following equation;

$$E_w = 2(K_a T_c / a)^{1/2} \quad [2.7]$$

where K_a = Anisotropy constant (described later)

If magnetostriction is a consideration, the equation is modified to;

$$E_w = 2(kT/a)^{1/2} (K_a + 3 \lambda_s \sigma / 2)^{1/2} \quad [2.8]$$

here λ_s = magnetostriction constant

Typical values of domain wall energies are on the order of 1-2 ergs/cm²

The domain wall thickness for the condition of minimum energy is given by the equation;

$$\delta = (\text{Constant}) \times a(E/K)^{1/2} \quad [2.9]$$

Typical calculated values of δ are about 10^3 Å or about 10^{-5} cm. With some soft magnetic materials the value may be about 10^{-6} cm while in some hard materials, the value may be on the order of 10^{-4} cm. or about one micron.

The whole array of domains will be arranged in such a way as to minimize the total energy of the system composed mainly of the above four energies.

PROOF OF THE EXISTENCE OF DOMAINS

The earliest experimental indication that domains existed was presented by Barkhausen (1919) who was able to pick up small voltages due to the discontinuous changes in the magnetizations in these regions. Barkhausen amplified these voltages

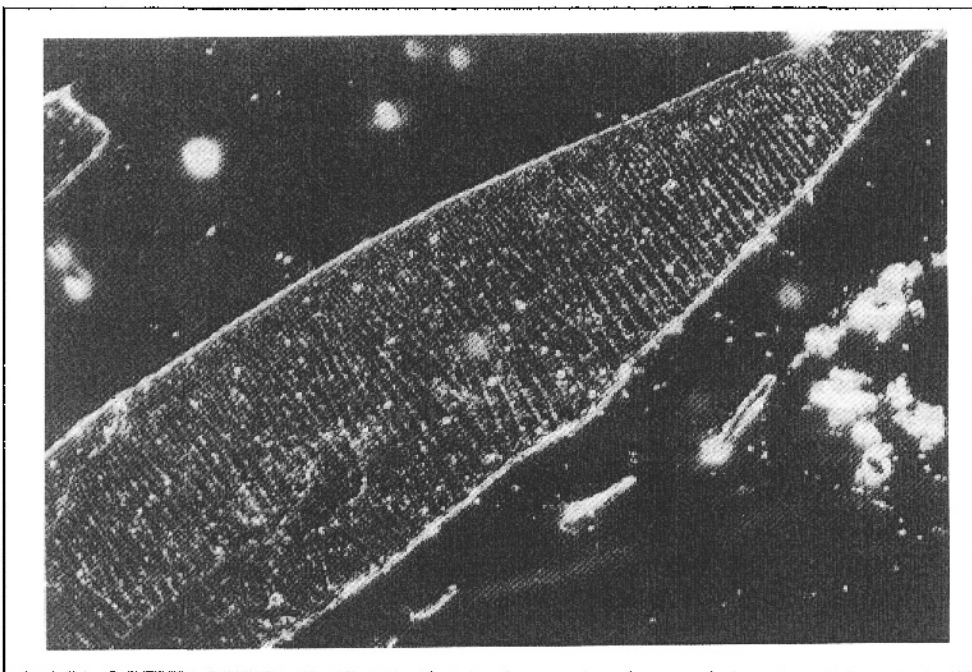


Figure 2.3a- Visualization of magnetic domains by means of the Bitter magnetic particle technique. The white stripes are the domain walls.

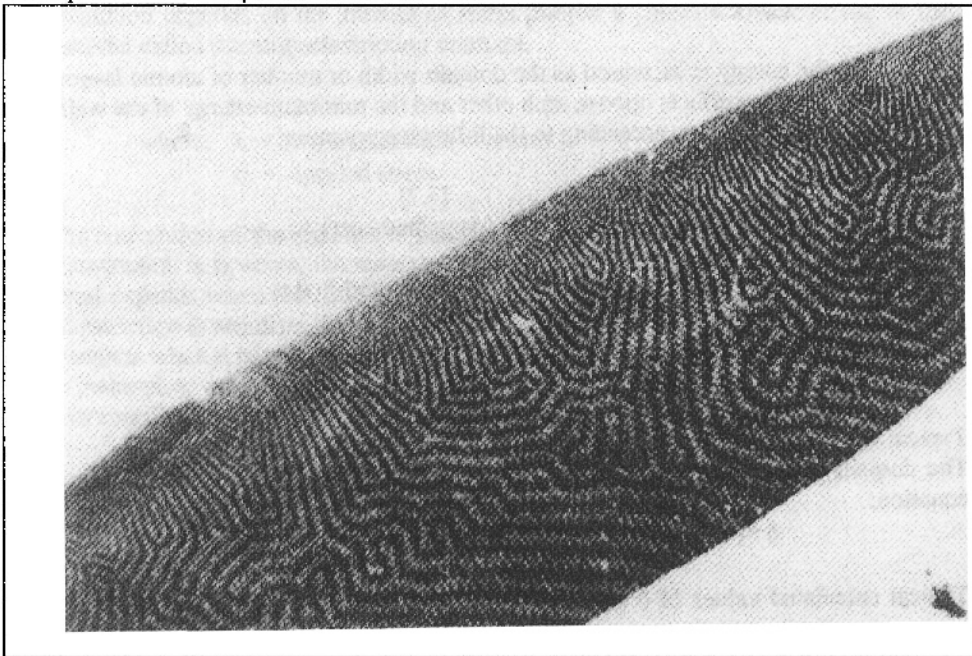


Figure 2.3b- Visualization of domains by Faraday rotation with polarized light.

many times and made them audible on a loudspeaker. Bitter (1931) was first able to visualize domains by spreading over the sample, a suspension of colloidal magnetite. The colloidal particles will be concentrated at the domain boundaries since large field gradients exist there. These arrangements are called Bitter patterns. Figure 2.3a exhibits domain walls using this method. This technique is limited to the static state since the powder prohibits true dynamic observations as well as temperature restrictions. Since light is an electromagnetic wave, it might be expected to interact with magnetic fields and moments. Many so-called magneto-optic effects have been observed. Through this interaction, domains have been made visible microscopically by both reflected and transmitted light. One technique employs a polarized light which has its plane of polarization rotated differently by domains with different magnetization direction. When the rotated light beam is sent through a polarizing medium called the analyzer, the domains will show up because of the contrast in light intensities of the neighboring domains. With reflected light, this phenomenon is known as the Kerr effect. With transmitted light, it is called Faraday rotation. Domain patterns in many magnetic materials have been photographed using this technique. Figure 2.3b is an example of the Faraday technique. Kaczmarek(1992) used the transverse and longitudinal Kerr Effects to observe domains in soft polycrystalline ferrites. Using a laser and fiber optics, he examined hysteresis effects that are in good relationship with bulk measurements

Domain patterns have also been viewed by TEM (Transmission Electron Microscopy). Van der Zaag (1992) studied domain structures in MnZn ferrites using this technique. He found that at a grain size up to 4 microns, the grains were monodomain while above this size, they were polydomain.

THE DYNAMIC BEHAVIOR OF DOMAINS

Two general mechanisms are involved in changing the magnetization in a domain and, therefore, changing the magnetization in a sample. The first mechanism acts by rotating the magnetization towards the direction of the field. Since this may involve rotating the magnetization from an axis of easy magnetization in a crystal to one of more difficult magnetization, a certain amount of anisotropy energy is required. The rotations can be small as indicated in Figure 2.4 or they can be almost the equivalent of a complete 180° reversal or flip if the crystal structure is uniaxial and if the magnetizing field is opposite to the original magnetization direction of the domain. The other mechanism for changing the domain magnetization is one in which the direction of magnetization remains the same, but the volumes occupied by the different domains may change. In this process, the domains whose magnetizations are in a direction closest to the field direction grow larger while those that are more unfavorably oriented shrink in size. Figure 2.5 shows this process which is called domain wall motion. The mechanism for domain wall motion starts in the domain wall. Present in the wall is a force (greatest with the moments in the walls that are at an angle of 90° to the applied field) that will tend to rotate those moments in line with the field. As a result, the center of the domain wall will move towards the domain opposed to the field. Thus, the area of the domain with favorable orientation will grow at the expense of its neighbor.

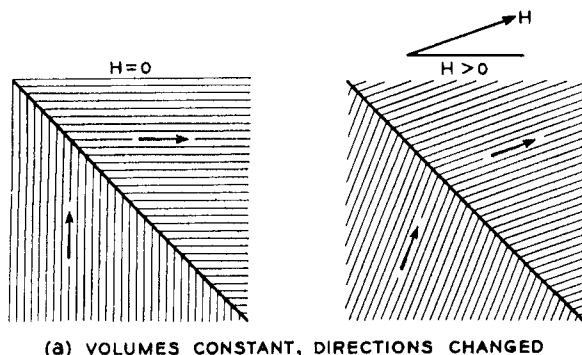


Figure 2.4- Change of domain magnetization by domain wall movement

BULK MATERIAL MAGNETIZATION

We have proceeded through the hierarchy of magnetic structures from the electron through the domain. Although domains are not physical entities such as atoms or crystal lattices and can only be visualized by special means, for the purpose of magnetic structure they are important in explaining the process of magnetization. We now can discuss why a material that has strongly oriented moments in a domain often has no resultant bulk material magnetization. We can also examine why this apparently "non-magnetic" material can be transformed into a strongly magnetic body by domain dynamics discussed above.

The answer, of course, resides in the fact that, if the material has been demagnetized, the domains point in all random directions so that there is complete cancellation and the resultant magnetization is zero (See Figure 2.6). The possible steps to complete orientation of the domains or magnetization of the material are also shown in Figure 2.6.

The Magnetization Curve

We are now ready to look at the bulk magnetic properties of a material. Thus far, the magnetic moment or the magnetization has been given in either atomic units (or Bohr magnetons) or in physical units based on action of magnets. How can we relate these to actual material properties? The Bohr magnetons were based on limiting values at absolute zero and since it was an atomic moment (ferromagnetism) or a resultant or combination of moments (ferrimagnetism), it was in the so called saturated condition. Having said that, there is a zero net moment in unmagnetized bulk materials, we can predict that there will be an infinite number of degrees of magnetization between the unmagnetized and saturation conditions. These extreme situations correspond, respectively, to random orientation of domain to complete alignment in one direction with the elimination of domain walls. If we start with a demagnetized specimen and increase the magnetic field, the bulk material will be progressively magnetized by the domain dynamics described previously.

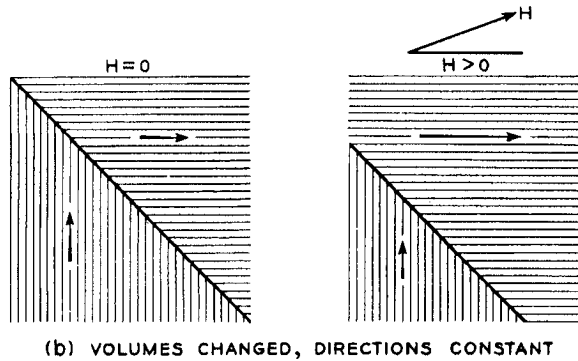


Figure 2.5-Change of domain magnetization by domain rotation

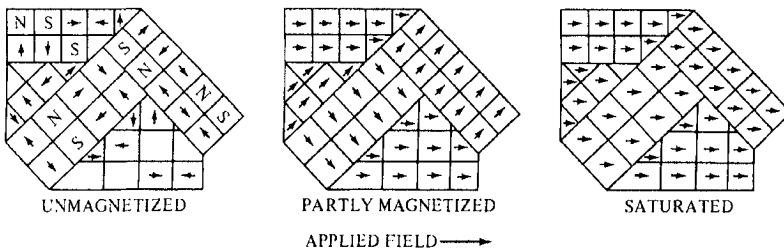


Figure 2.6-Stages in Magnetization of a sample containing several crystals

The magnetization of the sample will follow the course shown in Figure 2.7. The slope from the origin to a point on the curve or the ratio M/H has previously been defined as the magnetic susceptibility. This curve is called the magnetization curve. The curve is generally perceived as being made up of three major divisions. The lower section is called the initial susceptibility region in which there are reversible domain wall movements and rotations. Being reversible means that, after changing the magnetization slightly with an increase in field, the original magnetization condition can be returned if the field is reduced to the original value. The second stage of the magnetization curve in which the slope increases greatly is one in which irreversible domain wall motion occurs. The third section of the curve is one of irreversible domain rotations. Here, the slope is very flat indicating the large amount of energy that is required to rotate the remaining domain magnetization in line with the magnetic field.

Units for the Magnetization Curve

We have described the unit of magnetizing field H , from the interaction of magnetic poles. The unit was the oersted, defined as the field experienced at a distance of 1 cm from a unit pole. We have also described the magnetic moment, ml , from the

dipole. The pole density in poles per unit cross sectional area is the intensity of magnetization, M , whose units are the same as moment/unit volume = emu/cm^3 .

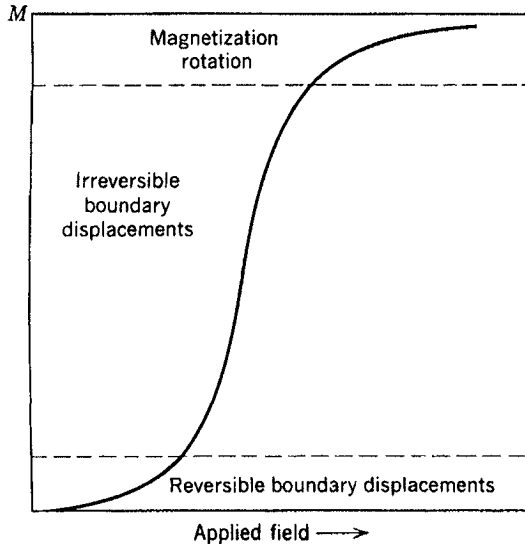


Figure 2.7-Domain dynamics during various parts of the magnetization curve. Source: Kittel, 1956

Conversion between Bohr Magnetons and Magnetization

There are times when we have to convert the moment in Bohr magnetons per atom, ion or formula unit in the case of ferrites to units of bulk magnetization, M , in emu/cm^3 or in units of emu/g . The former, M , is more important in magnetic design as part of the magnetic flux. The latter, σ , is important for materials research since with temperature changes, the density must be known accurately at each temperature. The pertinent formula is:

$$M = n \times \mu_B \times N_0 \times d/A \quad [2.10]$$

Where; N_0 = Number of atom/mole (6.02×10^{23})

A = Atomic weight

n = number of unpaired electron spins/atom

μ_B = value of a Bohr magneton

d = Density

The value $n \times \mu_B$ is the moment of the atom or ion in emu.

Flux Lines

Faraday found it convenient to liken magnetic behavior to a flow of endless lines of induction that indicated the direction and intensity of the flow. He called these lines flux lines and the number of lines per unit area the flux density or magnetic induc-

tion, B . The flux is composed of H lines and M lines. A schematic representation of the flux is given in Figure 2.8. Note that the lines traverse the sample, leave it at the North pole, and return at the South pole. In cgs units, the induction or flux density, B , is given by;

$$B = H + 4\pi M \quad [2.11]$$

A unit pole gives rise to a unit field everywhere on the surface of a sphere of unit radius. The area of this sphere is $4\pi \text{ cm}^2$. The cgs unit of induction is the gauss.

The units for the lines of induction or flux are known as maxwells or just plain "lines". Therefore, the units for flux density, B , are maxwells/cm². B can also be

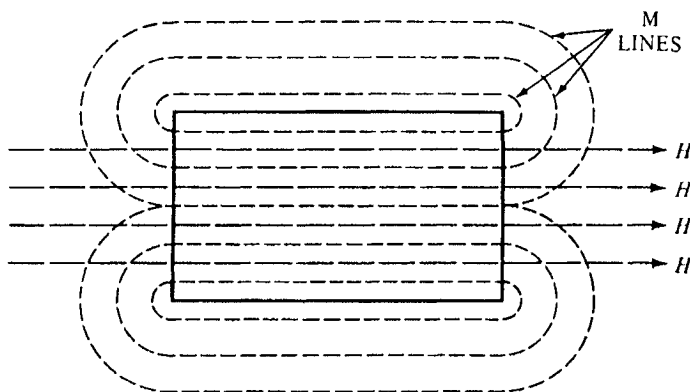


Figure 2.8-Magnetic flux lines composed of H (field) and M (magnetization lines)

defined by the voltage generated in a wire wound around a core of magnetic material in which there are known variations of flux with time.

Later in this book, as we get more involved with the magnetic circuit and applications, we will concentrate more heavily on the use of induction, B , by itself. The B lines and the H lines are each measured independently when a bulk material is magnetized.

Room Temperature Saturation Inductions of Magnetic Materials

To this point in our discussion, the magnetic moment has usually been measured at 0° K in order to allow the correlation with the number of Bohr magnetons to be made. The magnetization can also be expressed in terms of M_0 or the magnetization at 0° K. For practical applications, the room temperature values are much more important. In many cases, the total induction or flux density is measured with the field subtracted out to get the resultant $4\pi M_s$, which is often used interchangeably with B_s for soft magnetic materials. We have detailed the conversion from the Bohr magnetons to the magnetization. In a reverse manner, from value of $4\pi M_s$ (or B_s), the moment or number of Bohr magnetons can be calculated. The saturation induction of several magnetic materials are given at low temperatures and at room tem-

peratures in Table 3.1. Since we are stressing the component properties now, the latter values are of more concern.

MKSA Units

Earlier we stated that, as we got more involved with the circuit aspects of magnetism, it would be useful to introduce the mksa system of units. This may be a convenient time to do so. The mksa unit for magnetic flux is the weber. There are 10^8 maxwells per weber. The unit for flux density is then the weber/m² or as it is commonly known, the Tesla, T. There are 10^4 gaussess/Tesla. The unit for the

Table 3.1
Saturation Magnetizations of Various Magnetic Materials

<u>Material</u>	<u>Saturation (Gaussess)</u>
CoFe (49% Co, 49% Fe 2 V)	22,000
SiFe (3.25% Si)	18,000
NiFe (50% Ni, 50% Fe)	15,000
NiFe (79% Ni, 4% Mo, Balance Fe)	7,500
NiFe Powder (81% Ni, 2% Mo, Balance Fe)	8,000
Fe Powder	8,900
Ferrites	4,000-5,000
Amorphous Metal Alloy(Iron-Based)	15,000
Amorphous Metal Alloy (Co-based)	7,000
Nanocrystalline Materials (Iron-based)	12,000-16,000

magnetic field intensity, H, in the new units is the amp/m. H in oersteds is related to the mksa unit by the equation for the field generated by current through a coil containing N turns.

$$H = 4\pi NI/l \quad [2.12]$$

Where; N= number of turns

I = current in amps

l = length of magnetic path, cm.

Using this conversion, there are 12.57×10^{-3} oersteds/amp/m

HYSTERESIS LOOPS

In magnetic applications, we are interested in how much induction a certain applied field creates. In soft magnetic materials, we want a high induction for a low field. In this case, H is very small compared to $4\pi M$ and B is essentially equal to $4\pi M$. In the case of a permanent magnet, the H component can amount to from 50% or more of the total B. If we start with a demagnetized specimen and increase the magnetic field, the induction increases as shown in Figure 2.9. At high fields, the induction flattens out at a value called the saturation induction, B_s . If, after the material is saturated, the field is reduced to zero and then reversed in the opposite direction, the

original magnetization curve is not reproduced but a loop commonly called a hysteresis loop is obtained. Figure 2.9 shows such a hysteresis loop with the initial

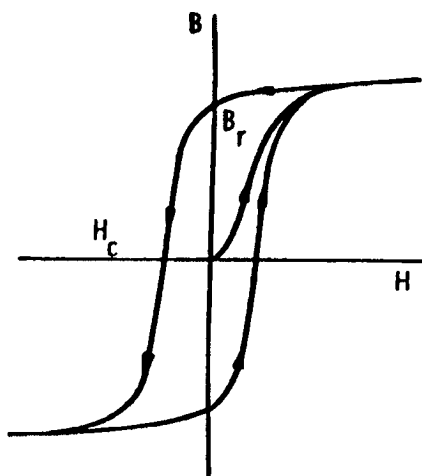


Figure 2.9-Initial magnetization curve and hysteresis loop

magnetization curve included. The arrows show the direction of travel. We notice that there is a lag in the induction with respect to the field. This lag is called hysteresis. As a result, the induction at a given field strength has 2 values and cannot be specified without a knowledge of the previous magnetic history of the sample. The area included in the hysteresis loop is a measure of the magnetic losses incurred in the cyclic magnetization process. The hysteresis losses can also be correlated with the irreversible domain dynamics we had previously mentioned. The value of the induction after saturation when the field is reduced to zero is called the remanent induction or remanence or retentivity, (B_r). The values of the reverse field needed after saturation to reduce the induction to zero is called the coercive force or coercivity, (H_c). The unit for H_c is the oersted and that for B_r is the gauss. Both of these properties are very important and we shall refer to them in almost every magnetic application.

Minor Loops

Thus far we have spoken of the magnetization process when the material is magnetized to saturation. This situation is not always true and loops can be produced when varying degrees of magnetization are produced. When the maximum induction is less than saturation, the loop is called a minor loop. The shape of these minor loops can be vastly different than the saturated loop. When an unmagnetized sample is progressively magnetized it follows the magnetization curve. If we stop part of the way up and then reduce the field to zero and repeat the process to the same value of reverse field the result is a minor loop. A minor loop is shown in Figure 2.10 along with the saturation loop.

PERMEABILITY

We previously defined the susceptibility as the ratio of M to H . For paramagnetics and diamagnetics, this parameter is quite useful. However, in ferromagnetics and ferrimagnetics we are concerned with the total flux density, B , and it is more convenient to define a very important new parameter, μ , the magnetic permeability

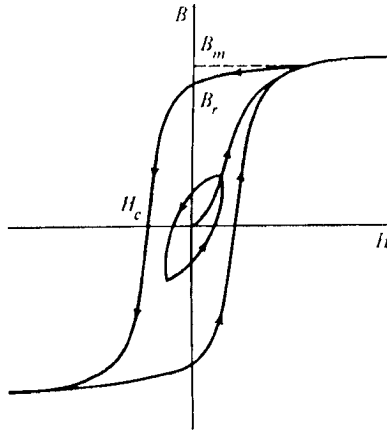


Figure 2.10 A minor hysteresis loop with the saturation loop

which is the ratio of induction, B to magnetizing field, H . However, this parameter can be measured under different sets of conditions. For example, if the magnetizing field is very low, approaching zero, the ratio will be called the initial permeability μ_0 . Its definition is given by;

$$\mu_0 = \lim_{B \rightarrow 0} (B/H) \quad [2.13]$$

This parameter will be an important in telecommunications applications where very low drive levels are involved. On the other hand, when the magnetizing field is sufficient to bring the B level up to the point of inflection, the highest permeability occurs. This can be seen by visualizing the permeability as the slope of the line from the origin to the end point of the excursion. Since the magnetization curve flattens out after the point, the μ will decrease. Often, it is important to know the position of the max permeability and the course of μ versus B . Such a curve is shown in Figure 2.11.

Factors Affecting the Permeability

Permeability is one of the most important parameters used in evaluating magnetic materials. Not only is it a function of the chemical composition and crystal struc-

ture but it is strongly dependent on microstructure, temperature, stress, time after demagnetization and several other factors. We shall discuss these in Chapter 6.

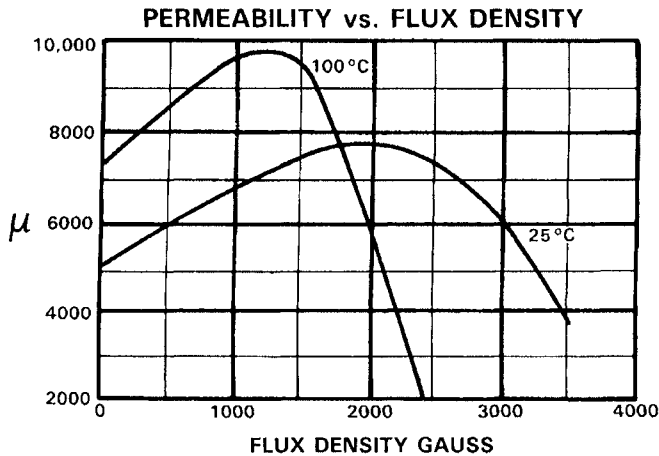


Figure 2.11-Variation of permeability as a function of flux density. Source, Magnetics 1989

In discussing the orientation of domains in a material in this chapter, we have previously briefly described two intrinsic parameters. These two properties were magnetocrystalline anisotropy and magnetostriction. Since they help in determining the equilibrium position of the domains and thus in the movement of these domains, they obviously affect the mechanism of magnetization which also includes the permeability.

MAGNETOCRYSTALLINE ANISOTROPY CONSTANTS

All ferromagnetic and ferromagnetic material possess to a lesser or greater degree a crystal direction or set of directions in which the magnetization prefers to be oriented. To rotate the magnetization from that easy direction requires an energy called the magnetocrystalline anisotropy energy. The energy is expressed in terms of certain anisotropy constants and the direction to which the magnetization is rotated. For the simple case of a uniaxial crystal such as a hexagonal structure, the relevant equation is;

$$E_k = K_1 \sin^2 \mu_B + K_2 \sin^4 \theta + \dots \quad 2.14]$$

where K_1 and K_2 = First and second anisotropy constants

θ = angle between the easy axis and magnetization

The conventional units for the anisotropy constants are ergs/cm³. In hexagonal ferrites, the easy axis is usually the hexagonal or c axis, although certain exceptions were noted earlier. Usually the first anisotropy constant is dominant and is suffi-

cient. For materials with cubic crystalline structure including the spinel ferrites, the anisotropy energy is given in terms of anisotropy constants. In this instance, however, the directions are given in terms of the direction cosines, α_n , which are the ratios of the individual components of the magnetization projected on each axis divided by the length of the magnetization or hypotenuse of the triangle. The appropriate equation for the anisotropy energy is;

$E_k = K_1(\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2) + K_2(\alpha_1^2 \alpha_2^2 \alpha_3^2) + \dots\dots\dots$ [2.15]

The direction that minimizes the energy will be the most preferred direction. The direction cosines for the principal direction in the cubic structure are;

	$\alpha_1(x)$	$\alpha_2(y)$	$\alpha_3(z)$
Cube edges	1	0	0
Face diagonal	$1/\sqrt{2}$	$1/\sqrt{2}$	0
Body diagonal	$1/\sqrt{3}$	$1/\sqrt{3}$	$1/\sqrt{3}$

When the anisotropy energy for each direction is calculated according to the above equation for cubic materials, the following values for E_k result;

- For cube edge (100) $E_k = 0$
- For face diagonal (110) $E_k = 1/4K_1$
- For body diagonal (111) $E_k = 1/3(K_1) + (1/27)K_2$

With few exceptions, K_1 will predominate and when K_1 is positive, the easy direction of magnetization will be the cube edge(100) direction and when K_1 is negative, the body diagonal (or so-called (111) direction in Miller indices)will be the preferred direction. In ferrites, with the exception of cobalt ferrites, the value of K_1 is negative, so that the cube diagonal is the easy direction in most ferrites. In soft materials where the domain motion is preferably unrestrained, the anisotropy or K_1 should be quite small in absolute magnitude. In most soft magnetic materials, that is indeed true. To determine the anisotropy constants, the measurements are made on single crystals that are oriented in the direction in which the anisotropy constant is to be measured. These constants will be correlated later with the properties of the polycrystalline ferrites. Later, in Chapter 5, these constants will be correlated with the properties of the polycrystalline magnetic materials.

In contrast to soft magnetic materials, for those designed to be permanent magnets, we usually want to take advantage of the affinity of the moments and the magnetization for a particular crystallographic direction. In hexagonal materials, as we have seen, this is the c axis. Therefore, hard or permanent magnet materials should have a very high anisotropy.

MAGNETOSTRICTION

Turning now to the magnetostriction constant, the magnetostrictive energy is given by:

$$E = \frac{3}{2} \lambda_s \sigma \quad [2.16]$$

where λ_s = saturation magnetostriction
 σ = applied stress

Here again, the energy should be minimized to give the domain freedom of motion. Through magnetostriction, stress, creates high-energy barriers to this motion. The magnetostriction constant or just the magnetostriction is really the sensitivity of the energy to the mechanical stresses. There are stresses produced in soft magnetic materials processing such as those due to thermal and mechanical operations which are difficult to avoid or correct. For good quality soft magnetic materials, a low magnetostriction is highly desirable. On the other hand, in magnetostrictive transducers for such applications as ultrasonic generators, the mechanical motion produced by the magnetic excitation through magnetostriction is used to good advantage. Of course, a high magnetostriction is required in this instance.

Since both anisotropy and magnetostriction are intrinsic properties of a material, by proper choice of the chemistry and crystal structure, we can strongly influence the magnetic parameters for a specific application.

IMPORTANT PROPERTIES FOR HARD MAGNETIC MATERIALS

For applications involving cyclic magnetization, the magnetization curves and hysteresis loops are the signatures of the material and contain many of the important parameters. In one major application, the magnetic material is not really cycled. This is the case for the permanent magnet (see Figure 9.1). Here, the core is magnetized to create the magnetic poles. When the magnetizing field is reduced to zero, the B level does not return to zero but follows the hysteresis loop to the induction value we have called the remanence. A certain amount of demagnetization occurs on removal of the field depending on the gap length, but with high remanence materials, the net residual can attain a value as high as 10,000 gauss. The coercive force of a uniaxial ferrite such as barium ferrite is given by;

$$H_c = 2K_1 / M_s \quad [2.17]$$

showing the need for a high crystal anisotropy and low saturation to aid in resisting demagnetization. Because the low M_s conflicts with the need for high remanence, a compromise is usually adopted. The field created from the residual strong poles forms a permanent magnet. Because of a strong uniaxial anisotropy, the coercive forces of permanent magnet materials are quite high ranging from about 500 oersteds for Alnico to 3,000 or higher for other materials. In the case of hard ferrites, the remanence is low because the saturation is so much lower than it is for metals. However, the coercive forces for hard ferrites are much higher than Alnico. In the gap, there are obviously no magnetization, M , lines so that the B lines consist of only H lines resulting from the M lines in the material. An important parameter for a permanent magnet in addition to the coercive force H_c , and the remanence B_r , is the maximum product of $B \times H$ occurring in the second quadrant of the hysteresis loop.

This unit is frequently known as the energy product and is measured (cgs) in gauss-oersteds or MGO (Mega Gauss-Oersteds) or in kJoules/m³.

Properties of Recording Materials

In materials used for cores or media for digital recording, we are concerned with creating a material that has two unique states of magnetization. This can easily be realized using the two stable states of magnetic saturation on the hysteresis loop. Such materials are often called square loop materials because of the type of hysteresis loop that is required. Loop properties such as B_s , B_r and H_c are important properties but there is an additional one known as the squareness ratio, B_r/B_s . This ratio was especially important in square loop memory cores, which have all but vanished. However, widely-used recording media such as $\gamma\text{-Fe}_2\text{O}_3$ use H_c as an important specified parameter.

SUMMARY

In this chapter we have examined the importance of domains and how their dynamics can affect the manner in which a material is magnetized. In addition we examined the fundamental units of bulk magnetization and induction in the magnetization curve and cyclically in a hysteresis loop. All of these processes were considered primarily under the influence of a D.C. drive. In the next chapter we shall see the changes that occur when the cyclic traversal is done at a rate such as that produced in the 50-60 Hz. line or mains frequency.

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